

CONTROLLED FUSION IN A FIELD REVERSED
CONFIGURATION AND DIRECT ENERGY CONVERSION

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1188, awarded by the Office of Naval Research. The Government has certain rights in this
5 invention.

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. application serial no. 10/077,661, filed
February 14, 2002, which is a continuation-in-part of U.S. application serial no. 09/902,934,
filed July 10, 2001, which is a continuation of U.S. application serial no. 08/953,130, filed
10 October 27, 1997, now abandoned, and a continuation-in-part of U.S. application serial no.
09/915,965, filed July 25, 2001, which is a continuation of U.S. application serial no.
09/878,046, filed June 8, 2001, now abandoned, which is a continuation-in-part of U.S.
application serial no. 08/953,130, filed October 27, 1997, now abandoned, which applications
are fully incorporated herein by reference.

15 This application is also related provisional U.S. application serial no. 60/277,374,
filed March 19, 2001, and provisional U.S. application serial no. 60/297,086, filed on June 8,
2001, which applications are fully incorporated herein by reference.

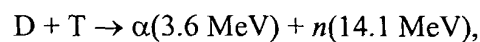
FIELD OF THE INVENTION

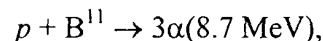
The invention relates generally to the field of plasma physics, and, in particular, to methods and apparatus for confining plasma to enable nuclear fusion and for converting energy from fusion products into electricity.

BACKGROUND OF THE INVENTION

Fusion is the process by which two light nuclei combine to form a heavier one. The fusion process releases a tremendous amount of energy in the form of fast moving particles. Because atomic nuclei are positively charged — due to the protons contained therein — there is a repulsive electrostatic, or Coulomb, force between them. For two nuclei to fuse, this repulsive barrier must be overcome, which occurs when two nuclei are brought close enough together where the short-range nuclear forces become strong enough to overcome the Coulomb force and fuse the nuclei. The energy necessary for the nuclei to overcome the Coulomb barrier is provided by their thermal energies, which must be very high. For example, the fusion rate can be appreciable if the temperature is at least of the order of 10^4 eV — corresponding roughly to 100 million degrees Kelvin. The rate of a fusion reaction is a function of the temperature, and it is characterized by a quantity called reactivity. The reactivity of a D-T reaction, for example, has a broad peak between 30 keV and 100 keV.

Typical fusion reactions include:





where D indicates deuterium, T indicates tritium, α indicates a helium nucleus, n indicates a neutron, p indicates a proton, He indicates helium, and B^{11} indicates Boron-11. The numbers in parentheses in each equation indicate the kinetic energy of the fusion products.

The first two reactions listed above — the D-D and D-T reactions — are neutronic, which means that most of the energy of their fusion products is carried by fast neutrons. The disadvantages of neutronic reactions are that (1) the flux of fast neutrons creates many problems, including structural damage of the reactor walls and high levels of radioactivity for most construction materials; and (2) the energy of fast neutrons is collected by converting their thermal energy to electric energy, which is very inefficient (less than 30%). The advantages of neutronic reactions are that (1) their reactivity peaks at a relatively low temperature; and (2) their losses due to radiation are relatively low because the atomic numbers of deuterium and tritium are 1.

The reactants in the other two equations — $D-He^3$ and $p-B^{11}$ — are called advanced fuels. Instead of producing fast neutrons, as in the neutronic reactions, their fusion products are charged particles. One advantage of the advanced fuels is that they create much fewer neutrons and therefore suffer less from the disadvantages associated with them. In the case of $D-He^3$, some fast neutrons are produced by secondary reactions, but these neutrons account for only about 10 per cent of the energy of the fusion products. The $p-B^{11}$ reaction is free of

fast neutrons, although it does produce some slow neutrons that result from secondary reactions but create much fewer problems. Another advantage of the advanced fuels is that their fusion products comprise charged particles whose kinetic energy may be directly convertible to electricity. With an appropriate direct energy conversion process, the energy of advanced fuel fusion products may be collected with a high efficiency, possibly in excess of 90 percent.

The advanced fuels have disadvantages, too. For example, the atomic numbers of the advanced fuels are higher (2 for He^3 and 5 for B^{11}). Therefore, their radiation losses are greater than in the neutronic reactions. Also, it is much more difficult to cause the advanced fuels to fuse. Their peak reactivities occur at much higher temperatures and do not reach as high as the reactivity for D-T. Causing a fusion reaction with the advanced fuels thus requires that they be brought to a higher energy state where their reactivity is significant. Accordingly, the advanced fuels must be contained for a longer time period wherein they can be brought to appropriate fusion conditions.

The containment time for a plasma is $\Delta t = r^2/D$, where r is a minimum plasma dimension and D is a diffusion coefficient. The classical value of the diffusion coefficient is $D_c = a_i^2 / \tau_{ie}$, where a_i is the ion gyroradius and τ_{ie} is the ion-electron collision time. Diffusion according to the classical diffusion coefficient is called classical transport. The Bohm diffusion coefficient, attributed to short-wavelength instabilities, is $D_B = (1/16)a_i^2\Omega_i$, where Ω_i is the ion gyrofrequency. Diffusion according to this relationship is called

anomalous transport. For fusion conditions, $D_B / D_c = (1/16)\Omega_i\tau_{ie} \cong 10^8$, anomalous transport results in a much shorter containment time than does classical transport. This relation determines how large a plasma must be in a fusion reactor, by the requirement that the containment time for a given amount of plasma must be longer than the time for the plasma to have a nuclear fusion reaction. Therefore, classical transport condition is more desirable in a fusion reactor, allowing for smaller initial plasmas.

In early experiments with toroidal confinement of plasma, a containment time of $\Delta t \cong r^2/D_B$ was observed. Progress in the last 40 years has increased the containment time to $\Delta t \cong 1000 r^2/D_B$. One existing fusion reactor concept is the Tokamak. The magnetic field of a Tokamak 68 and a typical particle orbit 66 are illustrated in Fig. 5. For the past 30 years, fusion efforts have been focussed on the Tokamak reactor using a D-T fuel. These efforts have culminated in the International Thermonuclear Experimental Reactor (ITER), illustrated in Fig. 7. Recent experiments with Tokamaks suggest that classical transport, $\Delta t \cong r^2/D_c$, is possible, in which case the minimum plasma dimension can be reduced from meters to centimeters. These experiments involved the injection of energetic beams (50 to 100 keV), to heat the plasma to temperatures of 10 to 30 keV. See W. Heidbrink & G. J. Sadler, 34 *Nuclear Fusion* 535 (1994). The energetic beam ions in these experiments were observed to slow down and diffuse classically while the thermal plasma continued to diffuse anomalously fast. The reason for this is that the energetic beam ions have a large gyroradius and, as such, are insensitive to fluctuations with wavelengths shorter than the ion gyroradius ($\lambda < a_i$). The

short-wavelength fluctuations tend to average over a cycle and thus cancel. Electrons, however, have a much smaller gyroradius, so they respond to the fluctuations and transport anomalously.

Because of anomalous transport, the minimum dimension of the plasma must be at least 2.8 meters. Due to this dimension, the ITER was created 30 meters high and 30 meters in diameter. This is the smallest D-T Tokamak-type reactor that is feasible. For advanced fuels, such as D-He³ and *p*-B¹¹, the Tokamak-type reactor would have to be much larger because the time for a fuel ion to have a nuclear reaction is much longer. A Tokamak reactor using D-T fuel has the additional problem that most of the energy of the fusion products energy is carried by 14 MeV neutrons, which cause radiation damage and induce reactivity in almost all construction materials due to the neutron flux. In addition, the conversion of their energy into electricity must be by a thermal process, which is not more than 30% efficient.

Another proposed reactor configuration is a colliding beam reactor. In a colliding beam reactor, a background plasma is bombarded by beams of ions. The beams comprise ions with an energy that is much larger than the thermal plasma. Producing useful fusion reactions in this type of reactor has been infeasible because the background plasma slows down the ion beams. Various proposals have been made to reduce this problem and maximize the number of nuclear reactions.

For example, U.S. Patent No. 4,065,351 to Jassby et al. discloses a method of producing counterstreaming colliding beams of deuterons and tritons in a toroidal confinement system. In U.S. Patent No. 4,057,462 to Jassby et al., electromagnetic energy is

injected to counteract the effects of bulk equilibrium plasma drag on one of the ion species.

The toroidal confinement system is identified as a Tokamak. In U.S. Patent No. 4,894,199 to Rostoker, beams of deuterium and tritium are injected and trapped with the same average velocity in a Tokamak, mirror, or field reversed configuration. There is a low-density cool
5 background plasma for the sole purpose of trapping the beams. The beams react because they have a high temperature, and slowing down is mainly caused by electrons that accompany the injected ions. The electrons are heated by the ions in which case the slowing down is minimal.

In none of these devices, however, does an equilibrium electric field play any part.

10 Further, there is no attempt to reduce, or even consider, anomalous transport.

Other patents consider electrostatic confinement of ions and, in some cases, magnetic confinement of electrons. These include U.S. Patent No. 3,258,402 to Farnsworth and U.S. Patent No. 3,386,883 to Farnsworth, which disclose electrostatic confinement of ions and inertial confinement of electrons; U.S. Patent No. 3,530,036 to Hirsch et al. and U.S. Patent
15 No. 3,530,497 to Hirsch et al. are similar to Farnsworth; U.S. Patent No. 4,233,537 to Limpaecher, which discloses electrostatic confinement of ions and magnetic confinement of electrons with multi-pole cusp reflecting walls; and U.S. Patent No. 4,826,646 to Bussard, which is similar to Limpaecher and involves point cusps. None of these patents consider electrostatic confinement of electrons and magnetic confinement of ions. Although there
20 have been many research projects on electrostatic confinement of ions, none of them have succeeded in establishing the required electrostatic fields when the ions have the required

density for a fusion reactor. Lastly, none of the patents cited above discuss a field reversed configuration magnetic topology.

The field-reversed configuration (FRC) was discovered accidentally around 1960 at the Naval Research Laboratory during theta pinch experiments. A typical FRC topology, wherein the internal magnetic field reverses direction, is illustrated in Fig. 8 and Fig. 10, and particle orbits in a FRC are shown in Fig. 11 and Fig. 14. Regarding the FRC, many research programs have been supported in the United States and Japan. There is a comprehensive review paper on the theory and experiments of FRC research from 1960-1988. *See* M. Tuszewski, 28 *Nuclear Fusion* 2033, (1988). A white paper on FRC development describes the research in 1996 and recommendations for future research. *See* L. C. Steinhauer et al., 30 *Fusion Technology* 116 (1996). To this date, in FRC experiments the FRC has been formed with the theta pinch method. A consequence of this formation method is that the ions and electrons each carry half the current, which results in a negligible electrostatic field in the plasma and no electrostatic confinement. The ions and electrons in these FRCs were contained magnetically. In almost all FRC experiments, anomalous transport has been assumed. *See, e.g.,* Tuszewski, beginning of section 1.5.2, at page 2072.

Thus, it is desirable to provide a fusion system having a containment system that tends to substantially reduce or eliminate anomalous transport of ions and electrons and an energy conversion system that converts the energy of fusion products to electricity with high efficiency.

SUMMARY OF THE INVENTION

The present invention is directed to a system that facilitates controlled fusion in a magnetic field having a field-reversed topology and the direct conversion of fusion product energies to electric power. The system, referred to herein as a plasma-electric power generation (PEG) system, preferably includes a fusion reactor having a containment system that tends to substantially reduce or eliminate anomalous transport of ions and electrons. In addition, the PEG system includes an energy conversion system coupled to the reactor that directly converts fusion product energies to electricity with high efficiency.

In one innovative aspect of the present invention, anomalous transport for both ions and electrons tends to be substantially reduced or eliminated. The anomalous transport of ions tends to be avoided by magnetically confining the ions in a magnetic field of field reversed configuration (FRC). For electrons, the anomalous transport of energy is avoided by tuning an externally applied magnetic field to develop a strong electric field, which confines the electrons electrostatically in a deep potential well. As a result, fusion fuel plasmas that can be used with the present confinement apparatus and process are not limited to neutronic fuels, but also advantageously include advanced or aneutronic fuels. For aneutronic fuels, fusion reaction energy is almost entirely in the form of charged particles, i.e., energetic ions, that can be manipulated in a magnetic field and, depending on the fuel, cause little or no radioactivity.

In another innovative aspect of the present invention, a direct energy conversion system is used to convert the kinetic energy of the fusion products directly into electric power

by slowing down the charged particles through an electro-magnetic field. Advantageously, the direct energy conversion system of the present invention has the efficiencies, particle-energy tolerances and electronic ability to convert the frequency and phase of the fusion output power of about 5 MHz to match the frequency of an external 60 Hertz power grid.

5 In a preferred embodiment, the fusion reactor's plasma containment system comprises a chamber, a magnetic field generator for applying a magnetic field in a direction substantially along a principle axis, and an annular plasma layer that comprises a circulating beam of ions. Ions of the annular plasma beam layer are substantially contained within the chamber magnetically in orbits and the electrons are substantially contained in an
10 electrostatic energy well. In one aspect of one preferred embodiment a magnetic field generator comprises a current coil. Preferably, the system further comprises mirror coils near the ends of the chamber that increase the magnitude of the applied magnetic field at the ends of the chamber. The system may also comprise a beam injector for injecting a neutralized ion beam into the applied magnetic field, wherein the beam enters an orbit due to the force
15 caused by the applied magnetic field. In another aspect of the preferred embodiments, the system forms a magnetic field having a topology of a field-reversed configuration.

In another preferred embodiment, the energy conversion system comprises inverse cyclotron converters (ICC) coupled to opposing ends of the fusion reactor. The ICC have a hollow cylinder-like geometry formed from multiple, preferably four or more equal, semi-
20 cylindrical electrodes with small, straight gaps extending there between. In operation, an oscillating potential is applied to the electrodes in an alternating fashion. The electric field E

within the ICC has a multi-pole structure and vanishes on the symmetry axes and increases linearly with radius; the peak value being at the gap.

In addition, the ICC includes a magnetic field generator for applying a uniform unidirectional magnetic field in a direction substantially opposite to that of the fusion reactor's containment system. At an end furthest from the fusion reactor power core the ICC includes an ion collector. In between the power core and the ICC is a symmetric magnetic cusp wherein the magnetic field of the containment system merges with the magnetic field of the ICC. An annular shaped electron collector is positioned about the magnetic cusp and electrically coupled to the ion collector.

In yet another preferred embodiment, product nuclei and charge-neutralizing electrons emerge as annular beams from both ends of the reactor power core with a density at which the magnetic cusp separates electrons and ions due to their energy differences. The electrons follow magnetic field lines to the electron collector and the ions pass through the cusp where the ion trajectories are modified to follow a substantially helical path along the length of the ICC. Energy is removed from the ions as they spiral past the electrodes, which are connected to a resonant circuit. The loss of perpendicular energy tends to be greatest for the highest energy ions that initially circulate close to the electrodes, where the electric field is strongest.

Other aspects and features of the present invention will become apparent from consideration of the following description taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments are illustrated by way of example, and not by way of limitation, in the figures of the accompanying drawings, in which like reference numerals refer to like components.

5 Fig. 1 shows an exemplary confinement chamber of the present invention.

Fig. 2 shows the magnetic field of a FRC.

Figs. 3A and 3B show, respectively, the diamagnetic and the counterdiamagnetic direction in a FRC.

Fig. 4 shows the colliding beam system of the present invention.

10 Fig. 5 shows a betatron orbit.

Figs. 6A and 6B show, respectively, the magnetic field and the direction of the gradient drift in a FRC.

Figs. 7A and 7B show, respectively, the electric field and the direction of the $\vec{E} \times \vec{B}$ drift in a FRC.

15 Figs. 8A, 8B and 8C show ion drift orbits.

Figs. 9A and 9B show the Lorentz force at the ends of a FRC.

Figs. 10A and 10B show the tuning of the electric field and the electric potential in the colliding beam system.

Fig. 11 shows a Maxwell distribution.

Figs. 12A and 12B show transitions from betatron orbits to drift orbits due to large-angle, ion-ion collisions.

Figs. 13 show A, B, C and D betatron orbits when small-angle, electron-ion collisions are considered.

5 Fig. 14 shows a neutralized ion beam as it is electrically polarized before entering a confining chamber.

Fig. 15 is a head-on view of a neutralized ion beam as it contacts plasma in a confining chamber.

10 Fig. 16 is a side view schematic of a confining chamber according to a preferred embodiment of a start-up procedure.

Fig. 17 is a side view schematic of a confining chamber according to another preferred embodiment of a start-up procedure.

Fig. 18 shows traces of B-dot probe indicating the formation of a FRC.

15 Fig. 19A shows a partial plasma-electric power generation system comprising a colliding beam fusion reactor coupled to an inverse cyclotron direct energy converter.

Fig. 19B shows an end view of the inverse cyclotron converter in Fig. 19A.

Fig. 19C shows an orbit of an ion in the inverse cyclotron converter.

20 Fig. 20A shows a partial plasma electric power generation system comprising a colliding beam fusion reactor coupled to an alternate embodiment of the inverse cyclotron converter.

Fig. 20B shows an end view of the inverse cyclotron converter in Fig. 20A.

Fig. 21A shows a particle orbit inside a conventional cyclotron.

Fig. 21B shows an oscillating electric field.

Fig. 21C shows the changing energy of an accelerating particle.

Fig. 22 shows an azimuthal electric field at gaps between the electrodes of the ICC
5 that is experienced by an ion with angular velocity.

Fig. 23 shows a focusing quadrupole doublet lens.

Figs. 24A and 24B show auxiliary magnetic-field-coil system.

Fig. 25 shows a 100 MW reactor.

Fig. 26 shows reactor support equipment.

10 Fig. 27 shows a plasma-thrust propulsion system.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

As illustrated in the figures, a plasma-electric power generation system of the present invention preferably includes a colliding beam fusion reactor coupled to a direct energy conversion system. As alluded to above, an ideal fusion reactor solves the problem of
15 anomalous transport for both ions and electrons. The solution to the problem of anomalous transport found herein makes use of a containment system with a magnetic field having a field reversed configuration (FRC). The anomalous transport of ions is avoided by magnetic confinement in the FRC in such a way that the majority of the ions have large, non-adiabatic orbits, making them insensitive to short-wavelength fluctuations that cause anomalous
20 transport of adiabatic ions. In particular, the existence of a region in the FRC where the

magnetic field vanishes makes it possible to have a plasma comprising a majority of non-adiabatic ions. For electrons, the anomalous transport of energy is avoided by tuning the externally applied magnetic field to develop a strong electric field, which confines them electrostatically in a deep potential well.

5 Fusion fuel plasmas that can be used with the present confinement apparatus and process are not limited to neutronic fuels such as D-D (Deuterium-Deuterium) or D-T (Deuterium-Tritium), but also advantageously include advanced or aneutronic fuels such as D-He³ (Deuterium-helium-3) or p-B¹¹ (hydrogen-Boron-11). (For a discussion of advanced fuels, see R. Feldbacher & M. Heindler, *Nuclear Instruments and Methods in Physics*
10 *Research*, A271(1988)JJ-64 (North Holland Amsterdam).) For such aneutronic fuels, the fusion reaction energy is almost entirely in the form of charged particles, i.e., energetic ions, that can be manipulated in a magnetic field and, depending on the fuel, cause little or no radioactivity. The D-He³ reaction produces an H ion and an He⁴ ion with 18.2 MeV energy while the p-B¹¹ reaction produces three He⁴ ions and 8.7 MeV energy. Based on theoretical
15 modeling for a fusion device utilizing aneutronic fuels, the output energy conversion efficiency may be as high as about 90%, as described by K. Yoshikawa, T. Noma and Y. Yamamoto in *Fusion Technology*, 19, 870 (1991), for example. Such efficiencies dramatically advance the prospects for aneutronic fusion, in a scalable (1-1000 MW), compact, low-cost configuration.

20 In a direct energy conversion process of the present invention, the charged particles of fusion products can be slowed down and their kinetic energy converted directly to electricity.

Advantageously, the direct energy conversion system of the present invention has the efficiencies, particle-energy tolerances and electronic ability to convert the frequency and phase of the fusion output power of about 5 MHz to match the frequency and phase of an external 60 Hertz power grid.

5 Fusion Containment System

Fig. 1 illustrates a preferred embodiment of a containment system 300 according to the present invention. The containment system 300 comprises a chamber wall 305 that defines therein a confining chamber 310. Preferably, the chamber 310 is cylindrical in shape, with principle axis 315 along the center of the chamber 310. For application of this
10 containment system 300 to a fusion reactor, it is necessary to create a vacuum or near vacuum inside the chamber 310. Concentric with the principle axis 315 is a betatron flux coil 320, located within the chamber 310. The betatron flux coil 320 comprises an electrical current carrying medium adapted to direct current around a long coil, as shown, which preferably comprises parallel windings of multiple separate coils and, most preferably, parallel windings
15 of about four separate coils, to form a long coil. Persons skilled in the art will appreciate that current through the betatron coil 320 will result in a magnetic field inside the betatron coil 320, substantially in the direction of the principle axis 315.

Around the outside of the chamber wall 305 is an outer coil 325. The outer coil 325 produce a relatively constant magnetic field having flux substantially parallel with principle
20 axis 315. This magnetic field is azimuthally symmetrical. The approximation that the magnetic field due to the outer coil 325 is constant and parallel to axis 315 is most valid away

from the ends of the chamber 310. At each end of the chamber 310 is a mirror coil 330. The mirror coils 330 are adapted to produce an increased magnetic field inside the chamber 310 at each end, thus bending the magnetic field lines inward at each end. (See Figs. 8 and 10.) As explained, this bending inward of the field lines helps to contain the plasma 335 in a
5 containment region within the chamber 310 generally between the mirror coils 330 by pushing it away from the ends where it can escape the containment system 300. The mirror coils 330 can be adapted to produce an increased magnetic field at the ends by a variety of methods known in the art, including increasing the number of windings in the mirror coils 330, increasing the current through the mirror coils 330, or overlapping the mirror coils 330
10 with the outer coil 325.

The outer coil 325 and mirror coils 330 are shown in Fig. 1 implemented outside the chamber wall 305; however, they may be inside the chamber 310. In cases where the chamber wall 305 is constructed of a conductive material such as metal, it may be advantageous to place the coils 325, 330 inside the chamber wall 305 because the time that it
15 takes for the magnetic field to diffuse through the wall 305 may be relatively large and thus cause the system 300 to react sluggishly. Similarly, the chamber 310 may be of the shape of a hollow cylinder, the chamber wall 305 forming a long, annular ring. In such a case, the betatron flux coil 320 could be implemented outside of the chamber wall 305 in the center of that annular ring. Preferably, the inner wall forming the center of the annular ring may
20 comprise a non-conducting material such as glass. As will become apparent, the chamber

310 must be of sufficient size and shape to allow the circulating plasma beam or layer 335 to rotate around the principle axis 315 at a given radius.

The chamber wall 305 may be formed of a material having a high magnetic permeability, such as steel. In such a case, the chamber wall 305, due to induced
5 countercurrents in the material, helps to keep the magnetic flux from escaping the chamber 310, “compressing” it. If the chamber wall were to be made of a material having low magnetic permeability, such as plexiglass, another device for containing the magnetic flux would be necessary. In such a case, a series of closed-loop, flat metal rings could be provided. These rings, known in the art as flux delimiters, would be provided within the
10 outer coils 325 but outside the circulating plasma beam 335. Further, these flux delimiters could be passive or active, wherein the active flux delimiters would be driven with a predetermined current to greater facilitate the containment of magnetic flux within the chamber 310. Alternatively, the outer coils 325 themselves could serve as flux delimiters.

As explained in further detail below, a circulating plasma beam 335, comprising
15 charged particles, may be contained within the chamber 310 by the Lorentz force caused by the magnetic field due to the outer coil 325. As such, the ions in the plasma beam 335 are magnetically contained in large betatron orbits about the flux lines from the outer coil 325, which are parallel to the principle axis 315. One or more beam injection ports 340 are also provided for adding plasma ions to the circulating plasma beam 335 in the chamber 310. In a
20 preferred embodiment, the injector ports 340 are adapted to inject an ion beam at about the same radial position from the principle axis 315 where the circulating plasma beam 335 is

contained (i.e., around a null surface described below). Further, the injector ports 340 are adapted to inject ion beams 350 (See Fig. 16) tangent to and in the direction of the betatron orbit of the contained plasma beam 335.

Also provided are one or more background plasma sources 345 for injecting a cloud
5 of non-energetic plasma into the chamber 310. In a preferred embodiment, the background plasma sources 345 are adapted to direct plasma 335 toward the axial center of the chamber 310. It has been found that directing the plasma this way helps to better contain the plasma 335 and leads to a higher density of plasma 335 in the containment region within the chamber 310.

10 Charged Particles in a FRC

Fig. 2 shows a magnetic field of a FRC 70. The system has cylindrical symmetry with respect to its axis 78. In the FRC, there are two regions of magnetic field lines: open 80 and closed 82. The surface dividing the two regions is called the separatrix 84. The FRC forms a cylindrical null surface 86 in which the magnetic field vanishes. In the central part 88 of the
15 FRC the magnetic field does not change appreciably in the axial direction. At the ends 90, the magnetic field does change appreciably in the axial direction. The magnetic field along the center axis 78 reverses direction in the FRC, which gives rise to the term “Reversed” in Field Reversed Configuration (FRC).

In Fig. 3A, the magnetic field outside of the null surface 94 is in a first direction 96.
20 The magnetic field inside the null surface 94 is in a second direction 98 opposite the first. If an ion moves in the direction 100, the Lorentz force 30 acting on it points towards the null

surface 94. This is easily appreciated by applying the right-hand rule. For particles moving in the diamagnetic direction 102, the Lorentz force always points toward the null surface 94. This phenomenon gives rise to a particle orbit called betatron orbit, to be described below.

Fig. 3B shows an ion moving in the counterdiamagnetic direction 104. The Lorentz force in this case points away from the null surface 94. This phenomenon gives rise to a type of orbit called a drift orbit, to be described below. The diamagnetic direction for ions is counterdiamagnetic for electrons, and vice versa.

Fig. 4 shows a ring or annular layer of plasma 106 rotating in the ions' diamagnetic direction 102. The ring 106 is located around the null surface 86. The magnetic field 108 created by the annular plasma layer 106, in combination with an externally applied magnetic field 110, forms a magnetic field having the topology of a FRC (The topology is shown in Fig 2).

The ion beam that forms the plasma layer 106 has a temperature; therefore, the velocities of the ions form a Maxwell distribution in a frame rotating at the average angular velocity of the ion beam. Collisions between ions of different velocities lead to fusion reactions. For this reason, the plasma beam layer or power core 106 is called a colliding beam system.

Fig. 5 shows the main type of ion orbits in a colliding beam system, called a betatron orbit 112. A betatron orbit 112 can be expressed as a sine wave centered on the null circle 114. As explained above, the magnetic field on the null circle 114 vanishes. The plane of the orbit 112 is perpendicular to the axis 78 of the FRC. Ions in this orbit 112 move in their

diamagnetic direction 102 from a starting point 116. An ion in a betatron orbit has two motions: an oscillation in the radial direction (perpendicular to the null circle 114), and a translation along the null circle 114.

Fig. 6A is a graph of the magnetic field 118 in a FRC. The horizontal axis of the graph represents the distance in centimeters from the FRC axis 78. The magnetic field is in kilogauss. As the graph depicts, the magnetic field 118 vanishes at the null circle radius 120.

As shown in Fig. 6B, a particle moving near the null circle will see a gradient 126 of the magnetic field pointing away from the null surface 86. The magnetic field outside the null circle is in a first direction 122, while the magnetic field inside the null circle is in a second direction 124 opposite to the first. The direction of a gradient drift is given by the cross product $\vec{B} \times \nabla B$, where ∇B is the gradient of the magnetic field; thus, it can be appreciated by applying the right-hand rule that the direction of the gradient drift is in the counterdiamagnetic direction, whether the ion is outside or inside the null circle 128.

Fig. 7A is a graph of the electric field 130 in a FRC. The horizontal axis of the graph represents the distance in centimeters from the FRC axis 78. The electric field is in volts/cm. As the graph depicts, the electric field 130 vanishes close to the null circle radius 120.

As shown if Fig. 7B, the electric field for ions is deconfining; it points in directions 132, 134 away from the null surface 86. The magnetic field, as before, is in opposite directions 122, 124 inside and outside of the null surface 86. It can be appreciated by

applying the right-hand rule that the direction of the $\vec{E} \times \vec{B}$ drift is in the diamagnetic direction 102, whether the ion is outside or inside the null surface 136.

Figs. 8A and 8B show another type of common orbit in a FRC, called a drift orbit 138. Drift orbits 138 can be outside of the null surface 114, as shown in Fig. 8A, or inside it, as shown in Fig. 8B. Drift orbits 138 rotate in the diamagnetic direction if the $\vec{E} \times \vec{B}$ drift dominates or in the counterdiamagnetic direction if the gradient drift dominates. The drift orbits 138 shown in Figs. 8A and 8B rotate in the diamagnetic direction 102 from starting point 116.

A drift orbit, as shown in Fig. 8C, can be thought of as a small circle rolling over a relatively bigger circle. The small circle 142 spins around its axis in the sense 144. It also rolls over the big circle 146 in the direction 102. The point 140 will trace in space a path similar to 138.

Figs. 9A and 9B show the direction of the Lorentz force at the ends of a FRC 151. In Fig. 9A, an ion is shown moving in the diamagnetic direction 102 with a velocity 148 in a magnetic field 150. It can be appreciated by applying the right-hand rule that the Lorentz force 152 tends to push the ion back into the region of closed field lines. In this case, therefore, the Lorentz force 152 is confining for the ions. In Fig. 9B, an ion is shown moving in the counterdiamagnetic direction with a velocity 148 in a magnetic field 150. It can be appreciated by applying the right-hand rule that the Lorentz force 152 tends to push the ion

into the region of open field lines. In this case, therefore, the Lorentz force 152 is deconfining for the ions.

Magnetic and Electrostatic Confinement in a FRC

A plasma layer 106 (see Fig. 4) can be formed in a FRC by injecting energetic ion
5 beams around the null surface 86 in the diamagnetic direction 102 of ions. (A detailed discussion of different methods of forming the FRC and plasma ring follows below.) In the circulating plasma layer 106, most of the ions have betatron orbits 112 (see Fig. 5), are energetic, and are non-adiabatic; thus, they are insensitive to short-wavelength fluctuations that cause anomalous transport.

10 In a plasma layer 106 formed in a FRC and under equilibrium conditions, the conservation of momentum imposes a relation between the angular velocity of ions ω_i and the angular velocity of electrons ω_e . The relation is

$$\omega_e = \omega_i \left[1 - \frac{\omega_i}{\Omega_0} \right], \text{ where } \Omega_0 = \frac{ZeB_0}{m_i c}. \quad (1)$$

In Eq. 1, Z is the ion atomic number, m_i is the ion mass, e is the electron charge, B_0 is the
15 magnitude of the applied magnetic field, and c is the speed of light. There are three free parameters in this relation: the applied magnetic field B_0 , the electron angular velocity ω_e , and the ion angular velocity ω_i . If two of them are known, the third can be determined from Eq.

1.

Because the plasma layer 106 is formed by injecting ion beams into the FRC, the angular velocity of ions ω_i is determined by the injection kinetic energy of the beam W_i , which is given by

$$W_i = \frac{1}{2} m_i V_i^2 = \frac{1}{2} m_i (\omega_i r_o)^2 \quad (2)$$

Here, $V_i = \omega_i r_o$, where V_i is the injection velocity of ions, ω_i is the cyclotron frequency of ions, and r_o is the radius of the null surface 86. The kinetic energy of electrons in the beam has been ignored because the electron mass m_e is much smaller than the ion mass m_i .

For a fixed injection velocity of the beam (fixed ω_i), the applied magnetic field B_0 can be tuned so that different values of ω_e are obtainable. As will be shown, tuning the external magnetic field B_0 also gives rise to different values of the electrostatic field inside the plasma layer. This feature of the invention is illustrated in Figs. 10A and 10B. Fig. 10A shows three plots of the electric field (in volts/cm) obtained for the same injection velocity, $\omega_i = 1.35 \times 10^7 \text{ s}^{-1}$, but for three different values of the applied magnetic field B_0 :

| Plot | Applied magnetic field (B_0) | electron angular velocity (ω_e) |
|------|----------------------------------|---|
| 154 | $B_0 = 2.77 \text{ kG}$ | $\omega_e = 0$ |
| 156 | $B_0 = 5.15 \text{ kG}$ | $\omega_e = 0.625 \times 10^7 \text{ s}^{-1}$ |
| 158 | $B_0 = 15.5 \text{ kG}$ | $\omega_e = 1.11 \times 10^7 \text{ s}^{-1}$ |

The values of ω_e in the table above were determined according to Eq. 1. One can appreciate that $\omega_e > 0$ means that $\Omega_0 > \omega_i$ in Eq. 1, so that electrons rotate in their counterdiamagnetic

direction. Fig. 10B shows the electric potential (in volts) for the same set of values of B_0 and ω_e . The horizontal axis, in Figs. 10A and 10B, represents the distance from the FRC axis 78, shown in the graph in centimeters. The electric field and electric potential depend strongly on ω_e .

5 The above results can be explained on simple physical grounds. When the ions rotate in the diamagnetic direction, the ions are confined magnetically by the Lorentz force. This was shown in Fig. 3A. For electrons, rotating in the same direction as the ions, the Lorentz force is in the opposite direction, so that electrons would not be confined. The electrons leave the plasma and, as a result, a surplus of positive charge is created. This sets up an
10 electric field that prevents other electrons from leaving the plasma. The direction and the magnitude of this electric field, in equilibrium, is determined by the conservation of momentum.

 The electrostatic field plays an essential role on the transport of both electrons and ions. Accordingly, an important aspect of this invention is that a strong electrostatic field is
15 created inside the plasma layer 106, the magnitude of this electrostatic field is controlled by the value of the applied magnetic field B_0 which can be easily adjusted.

 As explained, the electrostatic field is confining for electrons if $\omega_e > 0$. As shown in Fig. 10B, the depth of the well can be increased by tuning the applied magnetic field B_0 . Except for a very narrow region near the null circle, the electrons always have a small
20 gyroradius. Therefore, electrons respond to short-wavelength fluctuations with an

anomalously fast diffusion rate. This diffusion, in fact, helps maintain the potential well once the fusion reaction occurs. The fusion product ions, being of much higher energy, leave the plasma. To maintain charge quasi-neutrality, the fusion products must pull electrons out of the plasma with them, mainly taking the electrons from the surface of the plasma layer. The
5 density of electrons at the surface of the plasma is very low, and the electrons that leave the plasma with the fusion products must be replaced; otherwise, the potential well would disappear.

Fig. 11 shows a Maxwellian distribution 162 of electrons. Only very energetic electrons from the tail 160 of the Maxwell distribution can reach the surface of the plasma
10 and leave with fusion ions. The tail 160 of the distribution 162 is thus continuously created by electron-electron collisions in the region of high density near the null surface. The energetic electrons still have a small gyroradius, so that anomalous diffusion permits them to reach the surface fast enough to accommodate the departing fusion product ions. The energetic electrons lose their energy ascending the potential well and leave with very little
15 energy. Although the electrons can cross the magnetic field rapidly, due to anomalous transport, anomalous energy losses tend to be avoided because little energy is transported.

Another consequence of the potential well is a strong cooling mechanism for electrons that is similar to evaporative cooling. For example, for water to evaporate, it must be supplied the latent heat of vaporization. This heat is supplied by the remaining liquid
20 water and the surrounding medium, which then thermalize rapidly to a lower temperature faster than the heat transport processes can replace the energy. Similarly, for electrons, the

potential well depth is equivalent to water's latent heat of vaporization. The electrons supply the energy required to ascend the potential well by the thermalization process that re-supplies the energy of the Maxwell tail so that the electrons can escape. The thermalization process thus results in a lower electron temperature, as it is much faster than any heating process.

5 Because of the mass difference between electrons and protons, the energy transfer time from protons is about 1800 times less than the electron thermalization time. This cooling mechanism also reduces the radiation loss of electrons. This is particularly important for advanced fuels, where radiation losses are enhanced by fuel ions with an atomic number Z greater than 1; $Z > 1$.

10 The electrostatic field also affects ion transport. The majority of particle orbits in the plasma layer 106 are betatron orbits 112. Large-angle collisions, that is, collisions with scattering angles between 90° and 180° , can change a betatron orbit to a drift orbit. As described above, the direction of rotation of the drift orbit is determined by a competition between the $\vec{E} \times \vec{B}$ drift and the gradient drift. If the $\vec{E} \times \vec{B}$ drift dominates, the drift orbit
15 rotates in the diamagnetic direction. If the gradient drift dominates, the drift orbit rotates in the counterdiamagnetic direction. This is shown in Figs. 12A and 12B. Fig. 12A shows a transition from a betatron orbit to a drift orbit due to a 180° collision, which occurs at the point 172. The drift orbit continues to rotate in the diamagnetic direction because the $\vec{E} \times \vec{B}$ drift dominates. Fig. 12B shows another 180° collision, but in this case the electrostatic field

is weak and the gradient drift dominates. The drift orbit thus rotates in the counterdiamagnetic direction.

The direction of rotation of the drift orbit determines whether it is confined or not. A particle moving in a drift orbit will also have a velocity parallel to the FRC axis. The time it takes the particle to go from one end of the FRC to the other, as a result of its parallel motion, is called transit time; thus, the drift orbits reach an end of the FRC in a time of the order of the transit time. As shown in connection with Fig. 9A, the Lorentz force at the ends of the FRC is confining only for drift orbits rotating in the diamagnetic direction. After a transit time, therefore, ions in drift orbits rotating in the counterdiamagnetic direction are lost.

This phenomenon accounts for a loss mechanism for ions, which is expected to have existed in all FRC experiments. In fact, in these experiments, the ions carried half of the current and the electrons carried the other half. In these conditions the electric field inside the plasma was negligible, and the gradient drift always dominated the $\vec{E} \times \vec{B}$ drift. Hence, all the drift orbits produced by large-angle collisions were lost after a transit time. These experiments reported ion diffusion rates that were faster than those predicted by classical diffusion estimates.

If there is a strong electrostatic field, the $\vec{E} \times \vec{B}$ drift dominates the gradient drift, and the drift orbits rotate in the diamagnetic direction. This was shown above in connection with Fig. 12A. When these orbits reach the ends of the FRC, they are reflected back into the region of closed field lines by the Lorentz force; thus, they remain confined in the system.

The electrostatic fields in the colliding beam system may be strong enough, so that the $\vec{E} \times \vec{B}$ drift dominates the gradient drift. Thus, the electrostatic field of the system would avoid ion transport by eliminating this ion loss mechanism, which is similar to a loss cone in a mirror device.

Another aspect of ion diffusion can be appreciated by considering the effect of small-angle, electron-ion collisions on betatron orbits. Fig. 13A shows a betatron orbit 112; Fig. 13B shows the same orbit 112 when small-angle electron-ion collisions are considered 174; Fig. 13C shows the orbit of Fig. 13B followed for a time that is longer by a factor of ten 176; and Fig. 13D shows the orbit of Fig. 13B followed for a time longer by a factor of twenty 178. It can be seen that the topology of betatron orbits does not change due to small-angle, electron-ion collisions; however, the amplitude of their radial oscillations grows with time. In fact, the orbits shown in Figs. 13A to 13D fatten out with time, which indicates classical diffusion.

Formation of the FRC

Conventional procedures used to form a FRC primarily employ the theta pinch-field reversal procedure. In this conventional method, a bias magnetic field is applied by external coils surrounding a neutral gas back-filled chamber. Once this has occurred, the gas is ionized and the bias magnetic field is frozen in the plasma. Next, the current in the external coils is rapidly reversed and the oppositely oriented magnetic field lines connect with the previously frozen lines to form the closed topology of the FRC (see Fig. 2). This formation

process is largely empirical and there exists almost no means of controlling the formation of the FRC. The method has poor reproducibility and no tuning capability as a result.

In contrast, the FRC formation methods of the present invention allow for ample control and provide a much more transparent and reproducible process. In fact, the FRC formed by the methods of the present invention can be tuned and its shape as well as other properties can be directly influenced by manipulation of the magnetic field applied by the outer field coils 325. Formation of the FRC by methods of the present inventions also results in the formation of the electric field and potential well in the manner described in detail above. Moreover, the present methods can be easily extended to accelerate the FRC to reactor level parameters and high-energy fuel currents, and advantageously enables the classical confinement of the ions. Furthermore, the technique can be employed in a compact device and is very robust as well as easy to implement – all highly desirable characteristics for reactor systems.

In the present methods, FRC formation relates to the circulating plasma beam 335. It can be appreciated that the circulating plasma beam 335, because it is a current, creates a poloidal magnetic field, as would an electrical current in a circular wire. Inside the circulating plasma beam 335, the magnetic self-field that it induces opposes the externally applied magnetic field due to the outer coil 325. Outside the plasma beam 335, the magnetic self-field is in the same direction as the applied magnetic field. When the plasma ion current is sufficiently large, the self-field overcomes the applied field, and the magnetic field reverses

inside the circulating plasma beam 335, thereby forming the FRC topology as shown in Figs.

2 and 4.

The requirements for field reversal can be estimated with a simple model. Consider an electric current I_p carried by a ring of major radius r_0 and minor radius $a \ll r_0$. The magnetic field at the center of the ring normal to the ring is $B_p = 2\pi I_p / (cr_0)$. Assume that the ring current $I_p = N_p e (\Omega_0 / 2\pi)$ is carried by N_p ions that have an angular velocity Ω_0 . For a single ion circulating at radius $r_0 = V_0 / \Omega_0$, $\Omega_0 = eB_0 / m_i c$ is the cyclotron frequency for an external magnetic field B_0 . Assume V_0 is the average velocity of the beam ions. Field reversal is defined as

$$B_p = \frac{N_p e \Omega_0}{r_0 c} \geq 2B_0, \quad (3)$$

which implies that $N_p > 2 r_0 / \alpha_i$, and

$$I_p \geq \frac{e V_0}{\pi \alpha_i}, \quad (4)$$

where $\alpha_i = e^2 / m_i c^2 = 1.57 \times 10^{-16}$ cm and the ion beam energy is $\frac{1}{2} m_i V_0^2$. In the one-

dimensional model, the magnetic field from the plasma current is $B_p = (2\pi/c)i_p$, where i_p is

current per unit of length. The field reversal requirement is $i_p > e V_0 / \pi r_0 \alpha_i = 0.225$ kA/cm,

where $B_0 = 69.3$ G and $\frac{1}{2} m_i V_0^2 = 100$ eV. For a model with periodic rings and B_z is averaged

over the axial coordinate $\langle B_z \rangle = (2\pi/c)(I_p/s)$ (s is the ring spacing), if $s = r_0$, this model

would have the same average magnetic field as the one dimensional model with $i_p = I_p/s$.

Combined Beam/Betatron Formation Technique

A preferred method of forming a FRC within the confinement system 300 described above is herein termed the combined beam/betatron technique. This approach combines low energy beams of plasma ions with betatron acceleration using the betatron flux coil 320.

5 The first step in this method is to inject a substantially annular cloud layer of background plasma in the chamber 310 using the background plasma sources 345. Outer coil 325 produces a magnetic field inside the chamber 310, which magnetizes the background plasma. At short intervals, low energy ion beams are injected into the chamber 310 through the injector ports 340 substantially transverse to the externally applied magnetic field within
10 the chamber 310. As explained above, the ion beams are trapped within the chamber 310 in large betatron orbits by this magnetic field. The ion beams may be generated by an ion accelerator, such as an accelerator comprising an ion diode and a Marx generator. (see R.B. Miller, *An Introduction to the Physics of Intense Charged Particle Beams*, (1982)). As one of skill in the art can appreciate, the externally applied magnetic field will exert a Lorentz force
15 on the injected ion beam as soon as it enters the chamber 310; however, it is desired that the beam not deflect, and thus not enter a betatron orbit, until the ion beam reaches the circulating plasma beam 335. To solve this problem, the ion beams are neutralized with electrons and directed through a substantially constant unidirectional magnetic field before entering the chamber 310. As illustrated in Fig. 14, when the ion beam 350 is directed
20 through an appropriate magnetic field, the positively charged ions and negatively charged electrons separate. The ion beam 350 thus acquires an electric self-polarization due to the

magnetic field. This magnetic field may be produced by, e.g., a permanent magnet or by an electromagnet along the path of the ion beam. When subsequently introduced into the confinement chamber 310, the resultant electric field balances the magnetic force on the beam particles, allowing the ion beam to drift undeflected. Fig. 15 shows a head-on view of the ion beam 350 as it contacts the plasma 335. As depicted, electrons from the plasma 335 travel along magnetic field lines into or out of the beam 350, which thereby drains the beam's electric polarization. When the beam is no longer electrically polarized, the beam joins the circulating plasma beam 335 in a betatron orbit around the principle axis 315, as shown in Fig. 1 (see also Fig. 4).

When the plasma beam 335 travels in its betatron orbit, the moving ions comprise a current, which in turn gives rise to a poloidal magnetic self-field. To produce the FRC topology within the chamber 310, it is necessary to increase the velocity of the plasma beam 335, thus increasing the magnitude of the magnetic self-field that the plasma beam 335 causes. When the magnetic self-field is large enough, the direction of the magnetic field at radial distances from the axis 315 within the plasma beam 335 reverses, giving rise to a FRC. (See Figs. 2 and 4). It can be appreciated that, to maintain the radial distance of the circulating plasma beam 335 in the betatron orbit, it is necessary to increase the applied magnetic field from the outer coil 325 as the plasma beam 335 increases in velocity. A control system is thus provided for maintaining an appropriate applied magnetic field, dictated by the current through the outer coil 325. Alternatively, a second outer coil may be

used to provide the additional applied magnetic field that is required to maintain the radius of the plasma beam's orbit as it is accelerated.

To increase the velocity of the circulating plasma beam 335 in its orbit, the betatron flux coil 320 is provided. Referring to Fig. 16, it can be appreciated that increasing a current through the betatron flux coil 320, by Ampere's Law, induces an azimuthal electric field, E, inside the chamber 310. The positively charged ions in the plasma beam 335 are accelerated by this induced electric field, leading to field reversal as described above. When ion beams are added to the circulating plasma beam 335, as described above, the plasma beam 335 depolarizes the ion beams.

For field reversal, the circulating plasma beam 335 is preferably accelerated to a rotational energy of about 100 eV, and preferably in a range of about 75 eV to 125 eV. To reach fusion relevant conditions, the circulating plasma beam 335 is preferably accelerated to about 200 keV and preferably to a range of about 100 keV to 3.3 MeV.

FRC formation was successfully demonstrated utilizing the combined beam/betatron formation technique. The combined beam/betatron formation technique was performed experimentally in a chamber 1 m in diameter and 1.5 m in length using an externally applied magnetic field of up to 500 G, a magnetic field from the betatron flux coil 320 of up to 5 kG, and a vacuum of 1.2×10^{-5} torr. In the experiment, the background plasma had a density of 10^{13} cm^{-3} and the ion beam was a neutralized Hydrogen beam having a density of 1.2×10^{13}

cm⁻³, a velocity of 2×10^7 cm/s, and a pulse length of around 20 μ s (at half height). Field reversal was observed.

Betatron Formation Technique

Another preferred method of forming a FRC within the confinement system 300 is herein termed the betatron formation technique. This technique is based on driving the betatron induced current directly to accelerate a circulating plasma beam 335 using the betatron flux coil 320. A preferred embodiment of this technique uses the confinement system 300 depicted in Fig. 1, except that the injection of low energy ion beams is not necessary.

As indicated, the main component in the betatron formation technique is the betatron flux coil 320 mounted in the center and along the axis of the chamber 310. Due to its separate parallel windings construction, the coil 320 exhibits very low inductance and, when coupled to an adequate power source, has a low LC time constant, which enables rapid ramp up of the current in the flux coil 320.

Preferably, formation of the FRC commences by energizing the external field coils 325, 330. This provides an axial guide field as well as radial magnetic field components near the ends to axially confine the plasma injected into the chamber 310. Once sufficient magnetic field is established, the background plasma sources 345 are energized from their own power supplies. Plasma emanating from the guns streams along the axial guide field and spreads slightly due to its temperature. As the plasma reaches the mid-plane of the chamber

310, a continuous, axially extending, annular layer of cold, slowly moving plasma is established.

At this point the betatron flux coil 320 is energized. The rapidly rising current in the coil 320 causes a fast changing axial flux in the coil's interior. By virtue of inductive effects this rapid increase in axial flux causes the generation of an azimuthal electric field E (see Fig. 17), which permeates the space around the flux coil. By Maxwell's equations, this electric field E is directly proportional to the change in strength of the magnetic flux inside the coil, i.e.: a faster betatron coil current ramp-up will lead to a stronger electric field.

The inductively created electric field E couples to the charged particles in the plasma and causes a ponderomotive force, which accelerates the particles in the annular plasma layer. Electrons, by virtue of their smaller mass, are the first species to experience acceleration. The initial current formed by this process is, thus, primarily due to electrons. However, sufficient acceleration time (around hundreds of micro-seconds) will eventually also lead to ion current. Referring to Fig. 17, this electric field E accelerates the electrons and ions in opposite directions. Once both species reach their terminal velocities, current is carried about equally by ions and electrons.

As noted above, the current carried by the rotating plasma gives rise to a self magnetic field. The creation of the actual FRC topology sets in when the self magnetic field created by the current in the plasma layer becomes comparable to the applied magnetic field from the external field coils 325, 330. At this point magnetic reconnection occurs and the open field

lines of the initial externally produced magnetic field begin to close and form the FRC flux surfaces (see Figs. 2 and 4).

The base FRC established by this method exhibits modest magnetic field and particle energies that are typically not at reactor relevant operating parameters. However, the inductive electric acceleration field will persist, as long as the current in the betatron flux coil 320 continues to increase at a rapid rate. The effect of this process is that the energy and total magnetic field strength of the FRC continues to grow. The extent of this process is, thus, primarily limited by the flux coil power supply, as continued delivery of current requires a massive energy storage bank. However, it is, in principal, straightforward to accelerate the system to reactor relevant conditions.

For field reversal, the circulating plasma beam 335 is preferably accelerated to a rotational energy of about 100 eV, and preferably in a range of about 75 eV to 125 eV. To reach fusion relevant conditions, the circulating plasma beam 335 is preferably accelerated to about 200 keV and preferably to a range of about 100 keV to 3.3 MeV. When ion beams are added to the circulating plasma beam 335, as described above, the plasma beam 335 depolarizes the ion beams.

FRC formation utilizing the betatron formation technique was successfully demonstrated at the following parameter levels:

- Vacuum chamber dimensions: about 1 m diameter, 1.5 m length.
- Betatron coil radius of 10 cm.

- Plasma orbit radius of 20 cm.
- Mean external magnetic field produced in the vacuum chamber was up to 100 Gauss, with a ramp-up period of 150 μ s and a mirror ratio of 2 to 1. (Source: Outer coils and betatron coils).
- 5 • The background plasma (substantially Hydrogen gas) was characterized by a mean density of about 10^{13} cm^{-3} , kinetic temperature of less than 10 eV.
- The lifetime of the configuration was limited by the total energy stored in the experiment and generally was around 30 μ s.

The experiments proceeded by first injecting a background plasma layer by two sets
10 of coaxial cable guns mounted in a circular fashion inside the chamber. Each collection of 8 guns was mounted on one of the two mirror coil assemblies. The guns were azimuthally spaced in an equidistant fashion and offset relative to the other set. This arrangement allowed for the guns to be fired simultaneously and thereby created an annular plasma layer.

Upon establishment of this layer, the betatron flux coil was energized. Rising current
15 in the betatron coil windings caused an increase in flux inside the coil, which gave rise to an azimuthal electric field curling around the betatron coil. Quick ramp-up and high current in the betatron flux coil produced a strong electric field, which accelerated the annular plasma layer and thereby induced a sizeable current. Sufficiently strong plasma current produced a magnetic self-field that altered the externally supplied field and caused the creation of the

field reversed configuration. Detailed measurements with B-dot loops identified the extent, strength and duration of the FRC.

An example of typical data is shown by the traces of B-dot probe signals in Fig. 18.

The data curve A represents the absolute strength of the axial component of the magnetic

5 field at the axial mid-plane (75 cm from either end plate) of the experimental chamber and at

a radial position of 15 cm. The data curve B represents the absolute strength of the axial

component of the magnetic field at the chamber axial mid-plane and at a radial position of 30

cm. The curve A data set, therefore, indicates magnetic field strength inside of the fuel

plasma layer (between betatron coil and plasma) while the curve B data set depicts the

10 magnetic field strength outside of the fuel plasma layer. The data clearly indicates that the

inner magnetic field reverses orientation (is negative) between about 23 and 47 μ s, while the

outer field stays positive, i.e., does not reverse orientation. The time of reversal is limited by

the ramp-up of current in the betatron coil. Once peak current is reached in the betatron coil,

the induced current in the fuel plasma layer starts to decrease and the FRC rapidly decays.

15 Up to now the lifetime of the FRC is limited by the energy that can be stored in the

experiment. As with the injection and trapping experiments, the system can be upgraded to

provide longer FRC lifetime and acceleration to reactor relevant parameters.

Overall, this technique not only produces a compact FRC, but it is also robust and straightforward to implement. Most importantly, the base FRC created by this method can be

20 easily accelerated to any desired level of rotational energy and magnetic field strength. This

is crucial for fusion applications and classical confinement of high-energy fuel beams.

Fusion

Significantly, these two techniques for forming a FRC inside of a containment system 300 described above, or the like, can result in plasmas having properties suitable for causing nuclear fusion therein. More particularly, the FRC formed by these methods can be
5 accelerated to any desired level of rotational energy and magnetic field strength. This is crucial for fusion applications and classical confinement of high-energy fuel beams. In the confinement system 300, therefore, it becomes possible to trap and confine high-energy plasma beams for sufficient periods of time to cause a fusion reaction therewith.

To accommodate fusion, the FRC formed by these methods is preferably accelerated
10 to appropriate levels of rotational energy and magnetic field strength by betatron acceleration. Fusion, however, tends to require a particular set of physical conditions for any reaction to take place. In addition, to achieve efficient burn-up of the fuel and obtain a positive energy balance, the fuel has to be kept in this state substantially unchanged for prolonged periods of time. This is important, as high kinetic temperature and/or energy characterize a fusion
15 relevant state. Creation of this state, therefore, requires sizeable input of energy, which can only be recovered if most of the fuel undergoes fusion. As a consequence, the confinement time of the fuel has to be longer than its burn time. This leads to a positive energy balance and consequently net energy output.

A significant advantage of the present invention is that the confinement system and
20 plasma described herein are capable of long confinement times, i.e., confinement times that exceed fuel burn times. A typical state for fusion is, thus, characterized by the following

physical conditions (which tend to vary based on fuel and operating mode):

Average ion temperature: in a range of about 30 to 230 keV and preferably in a range of about 80 keV to 230 keV

5 Average electron temperature: in a range of about 30 to 100 keV and preferably in a range of about 80 to 100 keV

Coherent energy of the fuel beams (injected ion beams and circulating plasma beam): in a range of about 100 keV to 3.3 MeV and preferably in a range of about 300 keV to 3.3 MeV.

10 Total magnetic field: in a range of about 47.5 to 120 kG and preferably in a range of about 95 to 120 kG (with the externally applied field in a range of about 2.5 to 15 kG and preferably in a range of about 5 to 15 kG).

Classical Confinement time: greater than the fuel burn time and preferably in a range of about 10 to 100 seconds.

15 Fuel ion density: in a range of about 10^{14} to less than 10^{16} cm^{-3} and preferably in a range of about 10^{14} to 10^{15} cm^{-3} .

Total Fusion Power: preferably in a range of about 50 to 450 kW/cm (power per cm of chamber length)

20 To accommodate the fusion state illustrated above, the FRC is preferably accelerated to a level of coherent rotational energy preferably in a range of about 100 keV to 3.3 MeV, and more preferably in a range of about 300 keV to 3.3 MeV, and a level of magnetic field strength preferably in a range of about 45 to 120 kG, and more preferably in a range of about

90 to 115 kG. At these levels, high energy ion beams can be injected into the FRC and trapped to form a plasma beam layer wherein the plasma beam ions are magnetically confined and the plasma beam electrons are electrostatically confined.

Preferably, the electron temperature is kept as low as practically possible to reduce the amount of bremsstrahlung radiation, which can, otherwise, lead to radiative energy losses. The electrostatic energy well of the present invention provides an effective means of accomplishing this.

The ion temperature is preferably kept at a level that provides for efficient burn-up since the fusion cross-section is a function of ion temperature. High direct energy of the fuel ion beams is essential to provide classical transport as discussed in this application. It also minimizes the effects of instabilities on the fuel plasma. The magnetic field is consistent with the beam rotation energy. It is partially created by the plasma beam (self-field) and in turn provides the support and force to keep the plasma beam on the desired orbit.

Fusion Products

The fusion products are born in the power core predominantly near the null surface from where they emerge by diffusion towards the separatrix (see Figs. 2 and 4). This is due to collisions with electrons (as collisions with ions do not change the center of mass and therefore do not cause them to change field lines). Because of their high kinetic energy. (product ions have much higher energy than the fuel ions), the fusion products can readily cross the separatrix. Once they are beyond the separatrix, they can leave along the open field lines provided that they experience scattering from ion-ion collisions.

Although this collisional process does not lead to diffusion, it can change the direction of the ion velocity vector such that it points parallel to the magnetic field. These open field lines 80 connect the FRC topology of the core with the uniform applied field provided outside the FRC topology. Product ions emerge on different field lines, which they follow with a
5 distribution of energies. Advantageously, the product ions and charge-neutralizing electrons emerge in the form of rotating annular beams from both ends of the fuel plasma. For example for a 50 MW design of a p-B¹¹ reaction, these beams will have a radius of about 50 centimeters and a thickness of about 10 centimeters. In the strong magnetic fields found outside the separatrix 84 (typically around 100 kG), the product ions have an associated
10 distribution of gyro-radii that varies from a minimum value of about 1 cm to a maximum of around 3 cm for the most energetic product ions.

Initially the product ions have longitudinal as well as rotational energy characterized by $\frac{1}{2} M(v_{\text{par}})^2$ and $\frac{1}{2} M(v_{\text{perp}})^2$. v_{perp} is the azimuthal velocity associated with rotation around a field line as the orbital center. Since the field lines spread out after leaving the vicinity of
15 the FRC topology, the rotational energy tends to decrease while the total energy remains constant. This is a consequence of the adiabatic invariance of the magnetic moment of the product ions. It is well known in the art that charged particles orbiting in a magnetic field have a magnetic moment associated with their motion. In the case of particles moving along a slow changing magnetic field, there also exists an adiabatic invariant of the motion
20 described by $\frac{1}{2} M(v_{\text{perp}})^2/B$. The product ions orbiting around their respective field lines have a magnetic moment and such an adiabatic invariant associated with their motion. Since

B decreases by a factor of about 10 (indicated by the spreading of the field lines), it follows that v_{perp} will likewise decrease by about 3.2. Thus, by the time the product ions arrive at the uniform field region their rotational energy would be less than 5% of their total energy; in other words almost all the energy is in the longitudinal component.

5 Energy Conversion

The direct energy conversion system of the present invention comprises an inverse cyclotron converter (ICC) 420 shown in Figs. 19A and 20A coupled to a (partially illustrated) power core 436 of a colliding beam fusion reactor (CBFR) 410 to form a plasma-electric power generation system 400. A second ICC (not shown) may be disposed symmetrically to
10 the left of the CBFR 410. A magnetic cusp 486 is located between the CBFR 410 and the ICC 420 and is formed when the CBFR 410 and ICC 420 magnetic fields merge.

Before describing the ICC 420 and its operation in detail, a review of a typical cyclotron accelerator is provided. In conventional cyclotron accelerators, energetic ions with velocities perpendicular to a magnetic field rotate in circles. The orbit radius of the energetic
15 ions is determined by the magnetic field strength and their charge-to-mass ratio, and increases with energy. However, the rotation frequency of the ions is independent of their energy. This fact has been exploited in the design of cyclotron accelerators.

Referring to Fig. 21A, a conventional cyclotron accelerator 700 includes two mirror image C-shaped electrodes 710 forming mirror image D-shaped cavities placed in a
20 homogenous magnetic field 720 having field lines perpendicular to the electrodes' plane of symmetry, i.e., the plane of the page. An oscillating electric potential is applied between the

C-shaped electrodes (see Figure 21B). Ions I are emitted from a source placed in the center of the cyclotron 700. The magnetic field 720 is adjusted so that the rotation frequency of the ions matches that of the electric potential and associated electric field. If an ion I crosses the gap 730 between the C-shaped electrodes 710 in the same direction as that of the electric field, it is accelerated. By accelerating the ion I, its energy and orbit radius increase. When the ion has traveled a half-circle arc (experiencing no increase in energy), it crosses the gap 730 again. Now the electric field between the C-shaped electrodes 710 has reversed direction. The ion I is again accelerated, and its energy is further increased. This process is repeated every time the ion crosses the gap 730 provided its rotation frequency continues to match that of the oscillating electric field (see Fig. 21C). If on the other hand a particle crosses the gap 730 when the electric field is in the opposite direction it will be decelerated and returned to the source at the center. Only particles with initial velocities perpendicular to the magnetic field 720 and that cross the gaps 730 in the proper phase of the oscillating electric field will be accelerated. Thus, proper phase matching is essential for acceleration.

In principle, a cyclotron could be used to extract kinetic energy from a pencil beam of identical energetic ions. Deceleration of ions with a cyclotron, but without energy extraction has been observed for protons, as described by Bloch and Jeffries in *Phys. Rev.* 80, 305 (1950). The ions could be injected into the cavity such that they are brought into a decelerating phase relative to the oscillating field. All of the ions would then reverse the trajectory T of the accelerating ion shown in Fig. 21A. As the ions slow down due to interaction with the electric field, their kinetic energy is transformed into oscillating electric

energy in the electric circuit of which the cyclotron is part. Direct conversion to electric energy would be achieved, tending to occur with very high efficiency.

In practice, the ions of an ion beam would enter the cyclotron with all possible phases. Unless the varying phases are compensated for in the design of the cyclotron, half of the of
5 the ions would be accelerated and the other half decelerated. As a result, the maximum conversion efficiency would effectively be 50%. Moreover the annular fusion product ion beams discussed above are of an unsuitable geometry for the conventional cyclotron.

As discussed in greater detail below, the ICC of the present invention accommodates the annular character of the fusion product beams exiting the FRC of fusion reactor power
10 core, and the random relative phase of the ions within the beam and the spread of their energies.

Referring back to Fig. 19A, a portion of a power core 436 of the CBFR 410 is illustrated on the left side, wherein a plasma fuel core 435 is confined in a FRC 470 formed in part due to a magnetic field applied by outside field coils 425. The FRC 470 includes
15 closed field lines 482, a separatrix 484 and open field lines 480, which, as noted above, determines the properties of the annular beam 437 of the fusion products. The open field lines 480 extend away from the power core 436 towards the magnetic cusp 486. As noted above, fusion products emerge from the power core 436 along open field lines 480 in the form of an annular beam 437 comprising energetic ions and charge neutralizing electrons.

20 The geometry of the ICC 420 is like a hollow cylinder with a length of about five meters. Preferably, four or more equal, semi-cylindrical electrodes 494 with small, straight

gaps 497 make up the cylinder surface. In operation, an oscillating potential is applied to the electrodes 494 in an alternating fashion. The electric field E within the converter has a quadrupole structure as indicated in the end view illustrated in Fig. 19B. The electric field E vanishes on the symmetry axis and increases linearly with the radius; the peak value is at the gap 497.

In addition, the ICC 420 includes outside field coils 488 to form a uniform field within the ICC's hollow cylinder geometry. Because the current runs through the ICC field coils 488 in a direction opposite to the direction of the current running through the CBFR field coils 425, the field lines 496 in the ICC 420 run in a direction opposite to the direction of the open field lines 480 of the CBFR 410. At an end furthest from the power core 436 of the CBFR 410, the ICC 420 includes an ion collector 492.

In between the CBFR 410 and the ICC 420 is a symmetric magnetic cusp 486 wherein the open field lines 480 of the CBFR 410 merge with the field lines 496 of the ICC 420. An annular shaped electron collector 490 is positioned about the magnetic cusp 486 and electrically coupled to the ion collector 498. As discussed below, the magnetic field of the magnetic cusps 486 converts the axial velocity of the beam 437 to a rotational velocity with high efficiency. Fig. 19C illustrates a typical ion orbit 422 within the converter 420.

The CBFR 410 has a cylindrical symmetry. At its center is the fusion power core 436 with a fusion plasma core 435 contained in a FRC 470 magnetic field topology in which the fusion reactions take place. As noted, the product nuclei and charge-neutralizing electrons emerge as annular beams 437 from both ends of the fuel plasma 435. For example for a 50

MW design of a p-B¹¹ reaction, these beams will have a radius of about 50 cm and a thickness of about 10 cm. The annular beam has a density $n \cong 10^7\text{-}10^8 \text{ cm}^{-3}$. For such a density, the magnetic cusp 486 separates the electrons and ions. The electrons follow the magnetic field lines to the electron collector 490 and the ions pass through the cusp 486 where the ion trajectories are modified to follow a substantially helical path along the length of the ICC 420. Energy is removed from the ions as they spiral past the electrodes 494 connected to a resonant circuit (not shown). The loss of perpendicular energy is greatest for the highest energy ions that initially circulate close to the electrodes 494, where the electric field is strongest.

The ions arrive at the magnetic cusp 486 with the rotational energy approximately equal to the initial total energy, i.e., $\frac{1}{2} M v_p^2 \cong \frac{1}{2} M v_0^2$. There is a distribution of ion energies and ion initial radii r_0 when the ions reach the magnetic cusp 486. However, the initial radii r_0 tends to be approximately proportional to the initial velocity v_0 . The radial magnetic field and the radial beam velocity produce a Lorentz force in the azimuthal direction. The magnetic field at the cusp 486 does not change the particle energy but converts the initial axial velocity $v_p \cong v_0$ to a residual axial velocity v_z and an azimuthal velocity v_\perp , where $v_0^2 = v_z^2 + v_\perp^2$. The value of the azimuthal velocity v_\perp can be determined from the conservation of canonical momentum

$$P_\theta = M r_0 v_\perp - \frac{q B_0 r_0^2}{2c} = \frac{q B_0 r_0^2}{2c} \quad (5)$$

A beam ion enters the left hand side of the cusp 486 with $B_z = B_0$, $v_z = v_0$, $v_\perp = 0$ and $r = r_0$. It emerges on the right hand side of the cusp 486 with $r = r_0$, $B_z = -B_0$, $v_\perp = qB_0r_0/Mc$ and $v_z = \sqrt{v_0^2 - v_\perp^2}$

$$\frac{v_z}{v_0} = \sqrt{1 - \left(\frac{r_0 \Omega_0}{v_0} \right)^2} \quad (6)$$

5 where $\Omega_0 = \frac{qB_0}{Mc}$ is the cyclotron frequency. The rotation frequency of the ions is in a range of about 1-10 MHz, and preferably in a of about 5-10 MHz, which is the frequency at which power generation takes place.

In order for the ions to pass through the cusp 486, the effective ion gyro-radius must be greater than the width of the cusp 486 at the radius r_0 . It is quite feasible experimentally
10 to reduce the axial velocity by a factor of 10 so that the residual axial energy will be reduced by a factor of 100. Then 99% of the ion energy will be converted to rotational energy. The ion beam has a distribution of values for v_0 and r_0 . However, because r_0 is proportional to v_0 as previously indicated by the properties of the FRC based reactor, the conversion efficiency to rotational energy tends to be 99% for all ions.

15 As depicted in Fig. 19B, the symmetrical electrode structure of the ICC 420 of the present invention preferably includes four electrodes 494. A tank circuit (not shown) is connected to the electrode structures 494 so that the instantaneous voltages and electric fields are as illustrated. The voltage and the tank circuit oscillate at a frequency of $\omega = \Omega_0$. The

azimuthal electric field E at the gaps 497 is illustrated in Fig. 19B and Fig. 22. Fig. 22 illustrates the electric field in the gaps 497 between electrodes 494 and the field an ion experiences as it rotates with angular velocity Ω_0 . It is apparent that in a complete revolution the particle will experience alternately acceleration and deceleration in an order determined by the initial phase. In addition to the azimuthal electric field E_θ there is also a radial electric field E_r . The azimuthal field E_θ is maximum in the gaps 497 and decreases as the radius decreases. Fig 22 assumes the particle rotates maintaining a constant radius. Because of the gradient in the electric field the deceleration will always dominate over the acceleration. The acceleration phase makes the ion radius increase so that when the ion next encounters a decelerating electric field the ion radius will be larger. The deceleration phase will dominate independent of the initial phase of the ion because the radial gradient of the azimuthal electric field E_θ is always positive. As a result, the energy conversion efficiency is not limited to 50% due to the initial phase problem associated with conventional cyclotrons. The electric field E_r is also important. It also oscillates and produces a net effect in the radial direction that returns the beam trajectory to the original radius with zero velocity in the plane perpendicular to the axis as in Fig. 19C.

The process by which ions are always decelerated is similar to the principle of strong focusing that is an essential feature of modern accelerators as described in U.S. Patent No. 2,736,799. The combination of a positive (focusing) and negative lens (defocusing) is positive if the magnetic field has a positive gradient. A strong focusing quadrupole doublet

lens is illustrated in Fig. 23. The first lens is focusing in the x-direction and defocusing in the y-direction. The second lens is similar with x and y properties interchanged. The magnetic field vanishes on the axis of symmetry and has a positive radial gradient. The net results for an ion beam passing through both lenses is focusing in all directions independent of the order of passage.

Similar results have been reported for a beam passing through a resonant cavity containing a strong axial magnetic field and operating in the TE_{111} mode (*see* Yoshikawa et al.). This device is called a peniotron. In the TE_{111} mode the resonant cavity has standing waves in which the electric field has quadrupole symmetry. The results are qualitatively similar to some of the results described herein. There are quantitative differences in that the resonance cavity is much larger in size (10 meter length), and operates at a much higher frequency (155 MHz) and magnetic field (10 T). Energy extraction from the high frequency waves requires a rectenna. The energy spectrum of the beam reduces the efficiency of conversion. The existence of two kinds of ions is a more serious problem, but the efficiency of conversion is adequate for a D-He³ reactor that produces 15 MeV protons.

A single particle orbit 422 for a particle within the ICC 420 is illustrated in Fig. 19C. This result was obtained by computer simulation and a similar result was obtained for the peniotron. An ion entering at some radius r_0 spirals down the length of the ICC and after losing the initial rotational energy converges to a point on a circle of the same radius r_0 . The initial conditions are asymmetric; the final state reflects this asymmetry, but it is independent of the initial phase so that all particles are decelerated. The beam at the ion collector end of

the ICC is again annular and of similar dimensions. The axial velocity would be reduced by a factor of 10 and the density correspondingly increased. For a single particle an extracting efficiency of 99% is feasible. However, various factors, such as perpendicular rotational energy of the annular beam before it enters the converter, may reduce this efficiency by about 5%. Electric power extraction would be at about 1-10 MHz and preferably about 5-10 MHz, with additional reduction in conversion efficiency due to power conditioning to connect to a power grid.

As shown in Figs. 20A and 20B, alternative embodiments of the electrode structures 494 in the ICC 420 may include two symmetrical semi-circular electrodes and/or tapered electrodes 494 that taper towards the ion collector 492.

Adjustments to the ion dynamics inside the main magnetic field of the ICC 420 may be implemented using two auxiliary coil sets 500 and 510, as shown in Figs. 24A and 24B. Both coil sets 500 and 510 involve adjacent conductors with oppositely directed currents, so the magnetic fields have a short range. A magnetic-field gradient, as schematically illustrated in Fig. 24A, will change the ion rotation frequency and phase. A multi-pole magnetic field, as schematically illustrated in Fig. 24B, will produce bunching, as in a linear accelerator.

Reactor

Fig. 25 illustrates a 100 MW reactor. The generator cut away illustrates a fusion power core region having superconducting coils to apply a uniform magnetic field and a flux coil for formation of a magnetic field with field-reversed topology. Adjacent opposing ends of the fusion power core region are ICC energy converters for direct conversion of the kinetic

energy of the fusion products to electric power. The support equipment for such a reactor is illustrated in Fig. 26.

Propulsion System

5 Fig. 27 illustrate a plasma-thrust propulsion system 800. The system includes a FRC power core 836 in which a fusion fuel core 835 is contained and from both ends of which fusion products emerge in the form of an annular beam 837. An ICC energy converter 820 coupled to one end of the power core. A magnetic nozzle 850 is positioned adjacent the other end of the power core. The annular beam 837 of fusion products stream from one end of the fusion power core along field lines into the ICC for energy conversion and from the other end of the power core along field lines out of the nozzle for thrust T.

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 While the invention is susceptible to various modifications and alternative forms, a specific example thereof has been shown in the drawings and is herein described in detail. It should be understood, however, that the invention is not to be limited to the particular form disclosed, but to the contrary, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the appended claims.

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